(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Publication number: **0 310 438 A1**

(12) **EUROPEAN PATENT APPLICATION**

(21) Application number: 88309138.1

(22) Date of filing: 30.09.88

(51) Int. Cl.[4]: **G 02 B 6/34**

(30) Priority: 01.10.87 GB 8723050

(43) Date of publication of application: 05.04.89 Bulletin 89/14

(84) Designated Contracting States: AT BE CH DE ES FR GB GR IT LI LU NL SE

(71) Applicant: BRITISH TELECOMMUNICATIONS public limited company
British Telecom Centre, 81 Newgate Street
London EC1A 7AJ (GB)

(72) Inventor: Chamberlin, Giles Russell
22a Fonnereau Road
Ipswich Suffolk IP1 3JP (GB)

Payne, David Brian
Dalyn Chapel Lane
Wickham Market Suffolk IP13 0SD (GB)

McCartney, David John
5 South Close
Ipswich Suffolk (GB)

(74) Representative: Greenwood, John David et al
British Telecom Intellectual Property Unit 151 Gower Street
London WC1E 6BA (GB)

(54) **Optical filters.**

(57) An optical filter comprises a volume diffraction grating (1) provided within a waveguide. The grating (1) has a thickness T sufficient such that when an optical beam R is incident on the grating from outside the waveguide, wavelengths at or near the Bragg wavelength for the grating are diffracted and coupled into the waveguide, all but the first order interferences being substantially eliminated, whilst wavelengths away from the Bragg wavelength pass through the waveguide substantially undiffracted. The grating pitch L may be varied to permit tuning of the filter response.

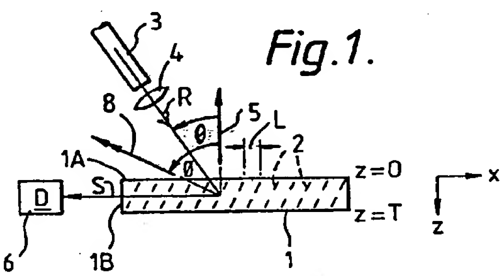


Fig.1.

EP 0 310 438 A1

Description

OPTICAL FILTERS

The invention relates to optical filters.

Volume reflection grating filters have been proposed for use in wavelength multiplexed optical systems. An example of such a filter is described in published UK Patent Application GB2151036. However, such reflection filters are difficult to implement in practice since an incident light beam is reflected back towards the launch direction making it difficult to couple the filtered wavelength into a detector or other output device. Furthermore, with reflection filters, once a desired wavelength has been selected by the grating, the filtered wavelength must generally be separately focussed into an output optical fibre for onward transmission.

In accordance with the present invention, an optical filter comprises an optical waveguide within which is provided a volume diffraction grating of refractive index modulations, the grating having a thickness sufficient such that when an optical beam is incident on the grating from outside the waveguide, wavelengths in a predetermined range at or near the Bragg wavelength for the grating are diffracted and coupled into the waveguide, all but the first order diffractions being substantially eliminated, whilst wavelengths away from the Bragg wavelength pass through the waveguide substantially undiffracted.

The filter according to the invention makes use of the wavelength selectively of a volume diffraction grating in which light at one wavelength can be efficiently diffracted whilst light of a second wavelength passes through the diffraction grating with no effect. The thickness of the grating enables diffraction of harmonic wavelength components to be eliminated (ie. higher than first order diffractions are suppressed). Preferably Q is greater than about 10 where $Q = 2\pi \lambda t/nd^2$, d being the fringe spacing. Moreover, by appropriately varying the grating thickness, the bandwidth of the range of wavelengths at or near the Bragg wavelength which are efficiently diffracted by the grating at a given angle of incidence of the input beam may be conveniently adjusted as desired. The present filter is further distinguished from the conventional reflection gratings of GB2151036 since the grating is provided in a waveguide. This enables a relatively thick (in the direction of grating normal) grating to be constructed providing the advantage of narrower bandwidth operation. In addition the direct coupling between the grating and waveguide results in a much simpler overall construction.

In order to achieve good coupling into the waveguide the grating modulations are conveniently established in planes extending at least in one direction normal to the preferred axis of propagation in the waveguide and extending in another direction, orthogonal to the one direction, at an angle $\pi/2 - \varphi$ with respect to the axis of propagation.

For coupling from an external optical beam into the waveguide the grating inclination φ should be less than $\pi/2$. In operation the optical beam should then be incident at an angle $\pi/2 - \theta$ to the axis of propagation, where $\theta < \varphi$ and $\theta = 2\varphi - \pi/2$. For a given grating thickness, the coupled bandwidth is narrower the closer θ approaches to $\pi/2$. For narrowband operation, it is therefore generally preferable for φ (and thus θ) to be as close to $\pi/2$ as possible.

However, as φ approaches $\pi/2$, the required inclination θ of the input beam also approaches $\pi/2$. In these circumstances, as θ increases, in the absence of efficient, index-matched coupling between the input beam and the waveguide, an increasing proportion of the input beam is simply reflected away from the waveguide before interaction with the grating leading to a corresponding reduction in the amount of light available for coupling into the waveguide. Practically, therefore, it is necessary to find a compromise. Without taking special steps towards index matching, it has been found that a satisfactory balance between narrowness of bandwidth and the proportion of coupled power is obtainable for angle φ of approximately $5\pi/12$ ($\theta \sim \pi/3$).

Preferably, the grating pitch varies along the waveguide, the wavelength band which is diffracted depending on the grating pitch at the position of incidence of the optical beam.

Preferably, the filter further comprises light guide means for guiding the light beam onto the grating, and tuning means to effect a relative movement of the light guide means and the grating, whereby the filter can be tuned to diffract a predetermined wavelength by suitably positioning the light guide means and the grating relative to one another.

The volume nature of the grating and the variation in the grating pitch allow a tunable filter to be conveniently implemented. Since the pitch varies along the waveguide a beam diffracted by one section of the grating will not be affected by other parts of the grating.

Furthermore, the filtered beam will exit from the grating along the waveguide and thus will not interfere with the input optical beam or the input beam optics. Similarly, the input beam will not interfere with the output beam or output beam optics leading to considerable ease of use.

The filter has particular advantage for use as a channel selection or a channel dropping filter in wavelength multiplexed (WDM) fibre optic networks.

The filter can be incorporated in an optical device including an auxiliary waveguide onto which the filter is mounted, the arrangement being such that a beam diffracted by the filter grating in use is coupled into the auxiliary waveguide.

In this specification, the term optical is intended to refer to that part of the electro-magnetic spectrum which is generally known as the visible region together with those parts of the infrared and ultraviolet regions at each end of the visible region which are capable of being transmitted by dielectric optical waveguides such as optical fibres.

Embodiments of an optical filter in accordance with the present invention and methods of operation will now be described with reference to the accompanying drawings, in which:-

Figure 1 is a schematic diagram of an embodiment of a filter according to the invention;

Figure 2 illustrates schematically an unslanted volume diffraction grating;

Figures 3 and 4 are graphs illustrating the wavelength and angular sensitivity of filters according to the invention;

Figure 5 is a graph showing the grating thickness required for 100% diffraction efficiency;

Figure 6 is a graph of the spectral response of a filter according to the invention;

Figure 7 illustrates an optical device including the filter of Figure 1; and

Figures 8 and 9 are schematic diagrams showing how a volume diffraction grating may be written in a waveguide.

The filter shown in Figure 1 comprises a film 1 defining a volume (phase) diffraction grating having a series of slanted diffraction planes 2, the normal 8 to the diffraction planes 2 extending in the zx plane of the film. In operation, an incident optical beam is transmitted along an optical fibre 3 via a collimating lens 4 which directs the beam onto a first surface 1A of the grating 1 at an angle θ to the film normal 5. The grating normal 8 is at an angle φ to the film normal 5. In this case components of the incident light beam at the relevant wavelength(s) are diffracted with the first order diffracted beam S being transmitted at right angles to the film normal 5. As shown in Figure 1, the diffracted beam S then passes via an end surface 1B of the grating waveguide 1 to an optical detector 6. Alternatively, for example, the diffracted beam could be coupled directly into another optical waveguide. The remaining wavelengths pass undiffracted straight through the grating 1.

As illustrated, the grating is of fixed pitch and consequently the wavelength response for a given incident angle θ is substantially the same wherever the input beam R is incident on the grating. It is possible to vary the pitch along the length of the grating to provide a so-called chirped grating. In such a case the grating pitch is made locally periodic over distances of the order of the width of the input beam but changes over longer distances. This enables the response of the filter to be tuned simply by translating the input optical fibre 3 and converging lens 4 lengthwise along the grating 1 so that the light beam R is incident on a section of the grating 1 with a pitch appropriate for the desired filtering response.

To explain the device response it is helpful to consider a simplified mathematical analysis as presented below.

The device shown in Figure 1 is not immediately amenable to analysis by using Kogelnik's coupled-wave theory ("Coupled wave theory for thick hologram gratings" H.Kogelnik, Bell System Technical Journal, vol 48, No.9, pp 2909 Nov.1969.) This theory requires the S wave to propagate in the z direction, which allows a solution to the wave equations to be found at the boundary $z = T$, after propagation through the thickness T of the grating (see Fig 1). However, this is not a fundamental physical limitation and rotation of the axes allows a solution to be obtained which is applicable to the present filter. For convenience, therefore, the geometry that will be analysed here is that of the unslanted grating 7 shown in Figure 2 (where $\varphi = 0$). The diffraction efficiency π for this arrangement is given by

15:54:45

$$\eta = \frac{\sin^2(\nu^2+\epsilon^2)^{1/2}}{(1 + \epsilon^2/\nu^2)}$$

where

$$\nu = \frac{\pi n_1 T}{\lambda \cos\theta}$$

and

$$\epsilon = \frac{\Delta\theta K T \sin\theta}{2\cos\theta}$$

or

$$\epsilon = \frac{-\Delta\lambda K^2 T}{8\pi n_0 \cos\theta}$$

and the grating constant K is given by

$$K = \frac{2\pi}{L}$$

and the Bragg condition is

$$\sin\theta = \frac{\lambda}{2L}$$

$\Delta\lambda$ and $\Delta\theta$ represent the deviations in λ and θ from the Bragg condition. From these results, it is apparent that appropriate values of grating pitch L, base refractive index n_o and index modulation n_1 may be selected such that the grating has 100% diffraction efficiency at a given wavelength λ, input at angle θ.

For a fixed set of grating parameters, it is possible to determine the angular and wavelength sensitivity of the filter structure. Figure 3 shows a series of response curves for different index modulations n_1 and for different incident angles θ illustrating how the bandwidth is narrowed as θ is increased and as the index modulation n_1 is decreased. Figure 4 shows a similar series of curves illustrating a corresponding change in angular bandwidth $\Delta\theta$. Figure 5 shows the grating thickness required to achieve 100% diffraction efficiency under the given conditions.

For a given index modulation n_1, the operational bandwidth is narrower as θ approaches $\pi/2$. However, as θ increases, particularly above about $\pi/3$, reflection losses at the boundary interface with the waveguide rise proportionately more rapidly. Therefore, unless special measures are taken to reduce such losses, for example by using suitable index matching techniques, there is little to be gained by increasing θ above $\pi/3$ (as can be seen from Figures 3 to 5).

From a straightforward geometrical analysis it can be seen that for light to be coupled into the waveguide then the grating slant angle φ must be greater than the angle of beam incidence θ and the two angles must be related such that $\theta = 2\varphi - \pi/2$. It will also be seen that the required grating thickness is reduced as $\varphi - \theta > 0$.

Given the above restrictions, for $\varphi = 5\pi/12$ and $\theta = \pi/3$, Figure 6 illustrates the spectral response of a filter according to the invention ~~with index modulation n_1 of 2×10^{-2} and a grating length of 200µm~~ with a centre wavelength of 1.3µm. The response is of the form sin(x)/x with a series of decreasing maxima. The relative amplitude of these peaks may be adjusted by varying the index modulation. (The analysis after Kogelnik assumes a sinusoidal variation.)

The volume diffraction grating may be provided in a waveguide which comprises a suitable holographic medium, such as for example dichromated gelatin (DCG). Waveguides comprising optically non-linear materials having stable non-linear states (ie non-linearity decay times relatively longer than the duration of an optical input requiring filtering) may also be used. Waveguides of the kind described in copending patent application GB 8722014 in the name of the present applicants may be suitable.

Figure 8 illustrates schematically how the slanted volume diffraction grating for a fixed wavelength filter may be written in a waveguide. In this case, the waveguide 80 is placed at an appropriate angle in the zone of interference 83 between two collimated laser beams 81,82. Figure 9 shows one method by which a chirped volume diffraction grating for a tunable filter may be produced. As before, a waveguide 90 with suitable

holographic properties is positioned similarly in the interference zone 93 between two laser beams 91,92. However, in this instance the beams are made to diverge to create the desired chirping in the fringes.

Filters according to the invention may conveniently be used with other optical components. Figure 7 illustrates an optical device incorporating the filter of Figure 1 together with an auxiliary waveguide comprising a conventional optical fibre. The filter (referenced 9) is incorporated into a polished coupler 10 with a conventional optical fibre 11. When a beam R is incident on the filter, the diffracted, filtered beam S is then coupled into the optical fibre 11 as indicated by the arrowed path.

Claims

1. An optical filter comprising an optical waveguide within which is provided a volume diffraction grating of refractive index modulations, the grating having a thickness sufficient such that when an optical beam is incident on the grating from outside the waveguide, wavelengths at or near the Bragg wavelength for the grating are diffracted and coupled into the waveguide, all but the first order interferences being substantially eliminated, whilst wavelengths away from the Bragg wavelength pass through the waveguide substantially undiffracted.

2. An optical filter according to claim 1, wherein the grating modulations are established in planes extending at least in one direction substantially normal to the preferred axis of propagation in the waveguide and extending in another direction, orthogonal to the one direction, at an angle $\pi/2 - \varphi$ with respect to the axis of propagation, where φ is less than $\pi/2$.

3. An optical filter according to claim 2, wherein φ is not more than $5\pi/12$.

4. An optical filter according to any preceding claim wherein the grating pitch varies along the waveguide.

5. An optical filter according to any preceding claim further comprising light guide means for guiding a light beam onto the grating, and tuning means to effect a relative movement of the light guide means and grating, whereby the filter can be tuned to diffract a predetermined wavelength by suitably positioning the light guide means and grating relative to one another.

6. An optical filter according to any preceding claim wherein the waveguide comprises an optical fibre having a core containing an optically non-linear medium.

7. A filter substantially as hereinbefore described with reference to the accompanying drawings.

8. An optical device comprising a filter according to any of the preceding claims, and an auxiliary waveguide onto which the filter is mounted, the arrangement being such that a beam diffracted by the filter grating in use is coupled into the auxiliary waveguide.

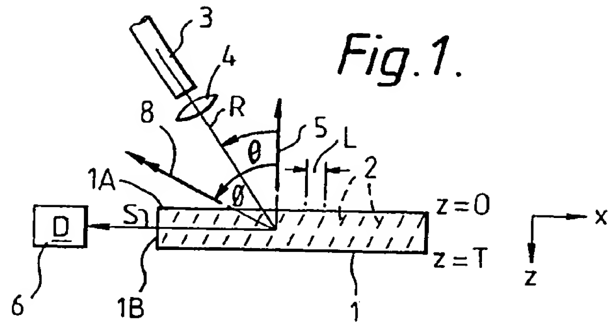


Fig.1.

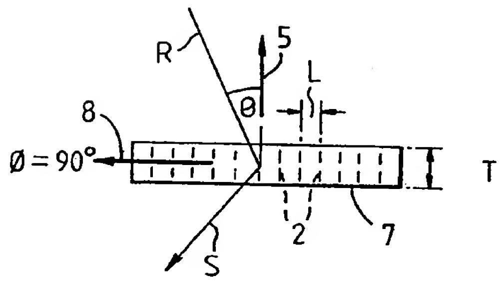


Fig.2.

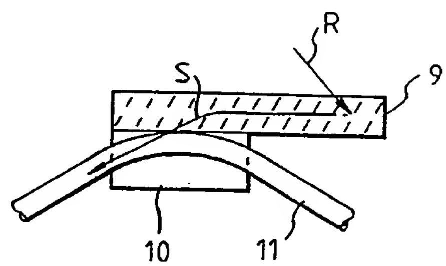


Fig.7.

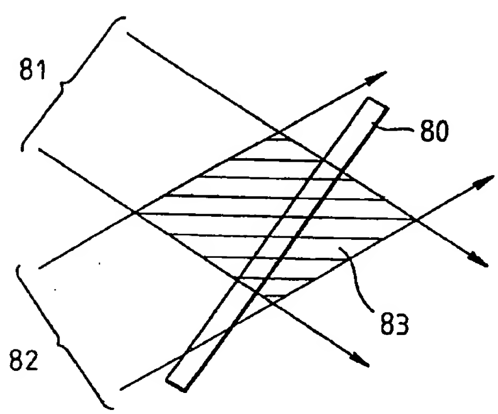


Fig.8.

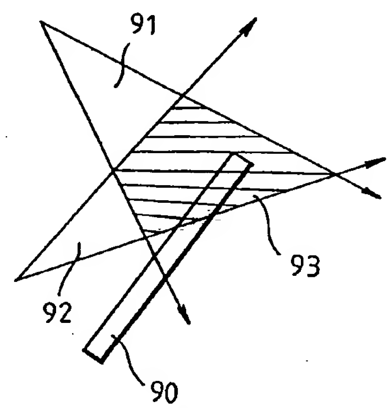


Fig.9.

Fig.3.

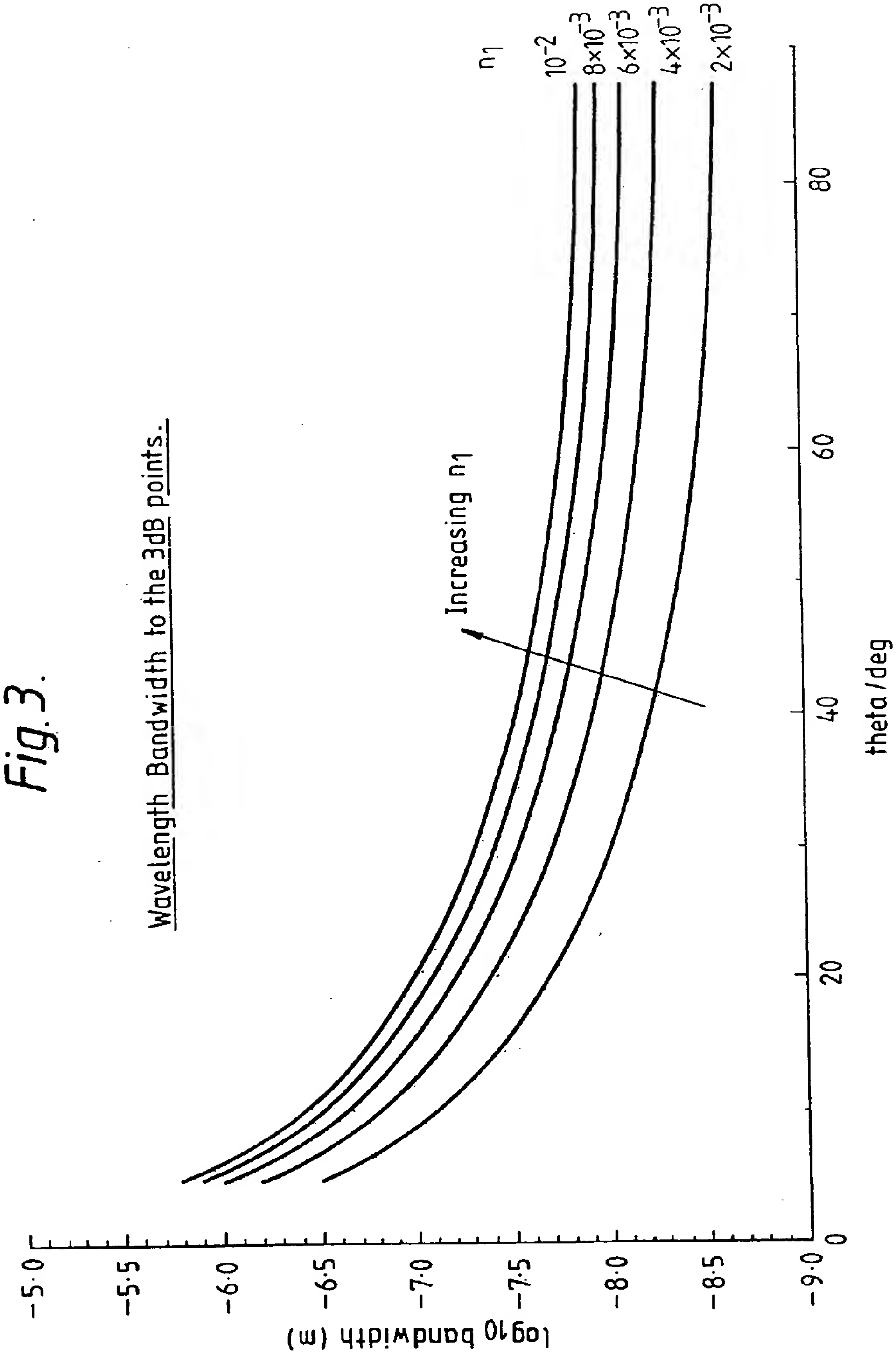

Wavelength Bandwidth to the 3dB points.
log10 bandwidth (m)
-5·0
-5·5
-6·0
-6·5
-7·0
-7·5
-8·0
-8·5
-9·0
0
20
40
60
80
theta /deg
Increasing n1
n1
10-2
8×10-3
6×10-3
4×10-3
2×10-3

Fig. 4.

Angular Bandwidth to the 3dB points.

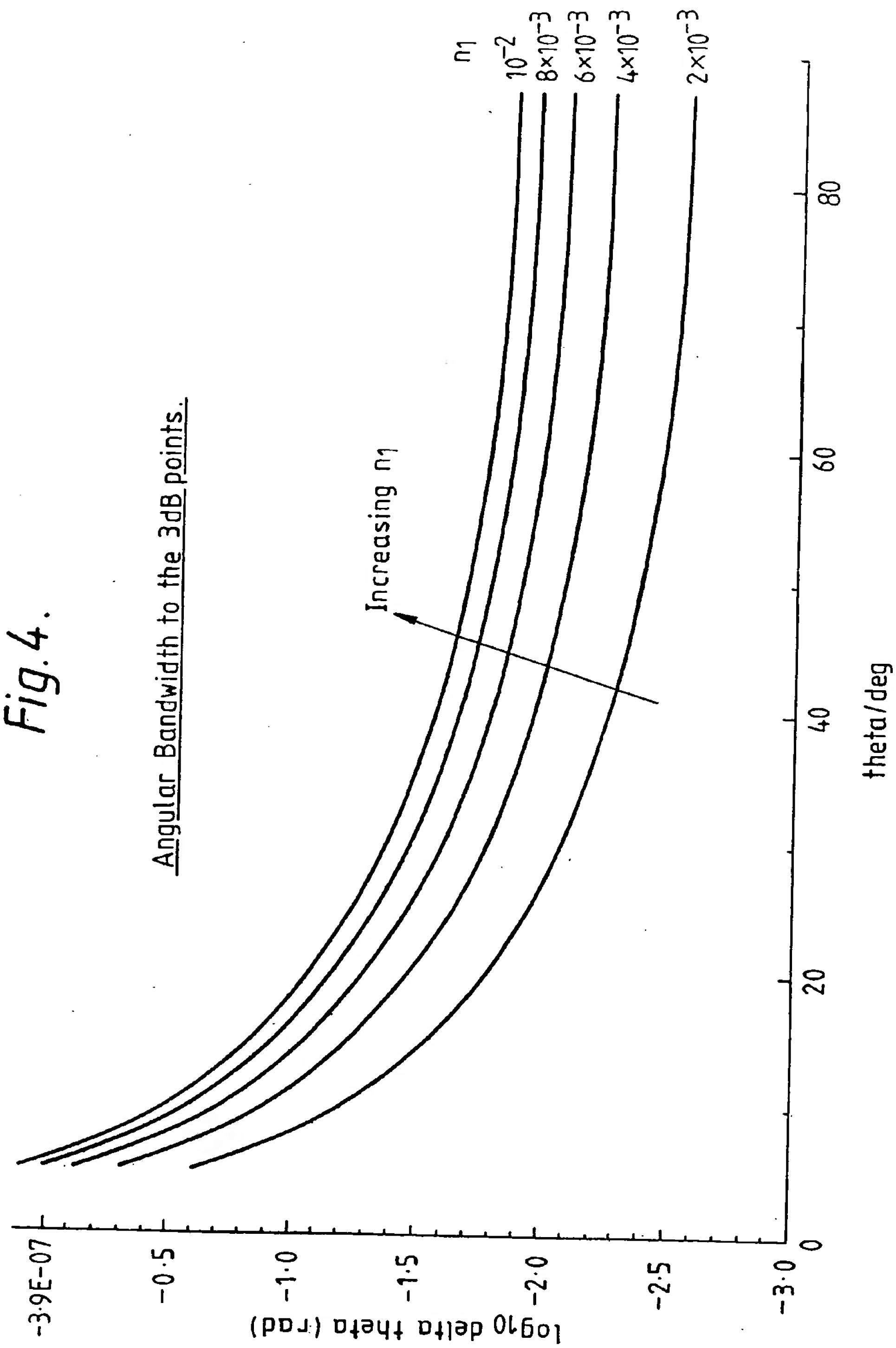


Fig.5.

Grating thickness for 100% Efficiency.

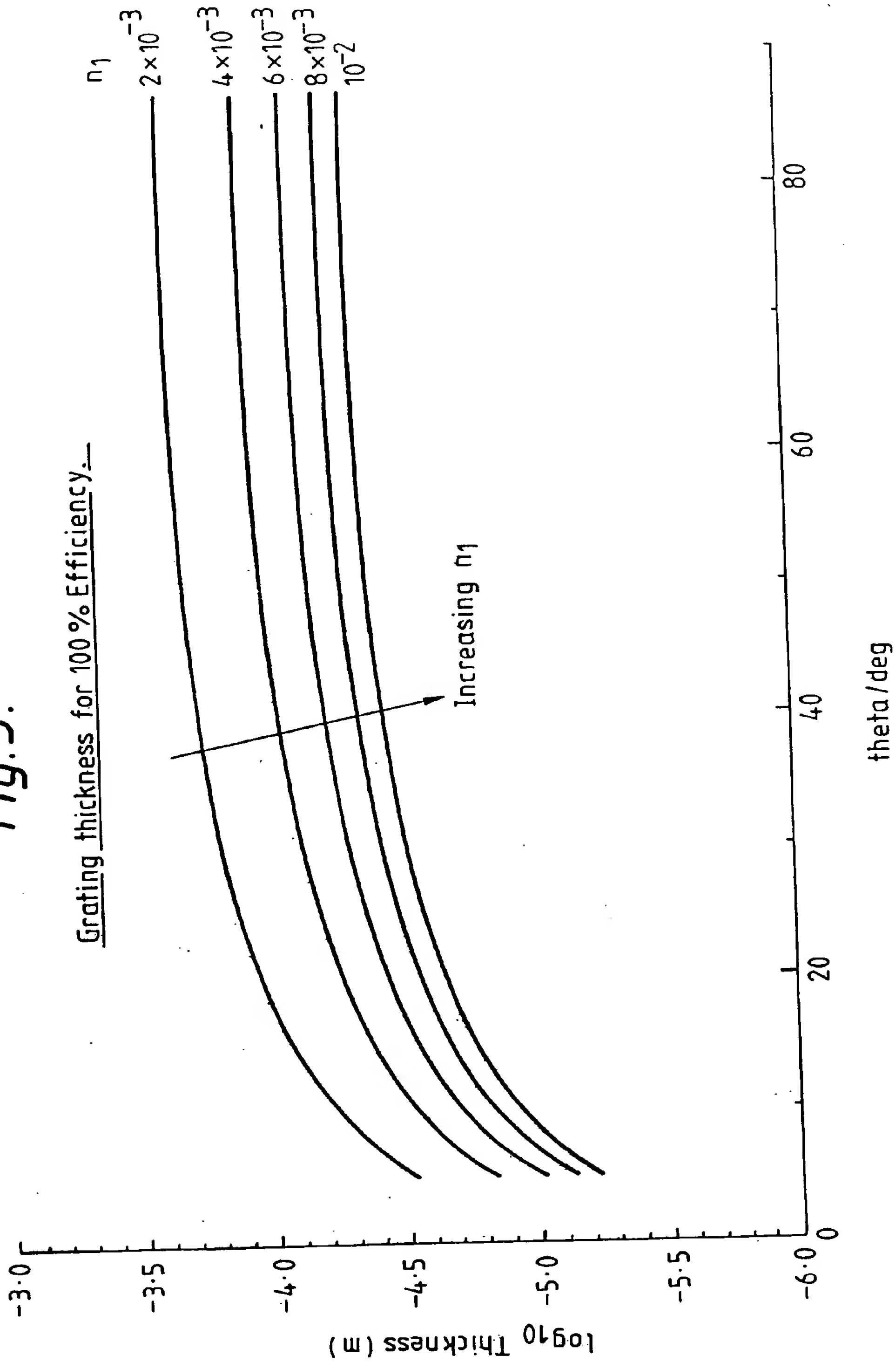
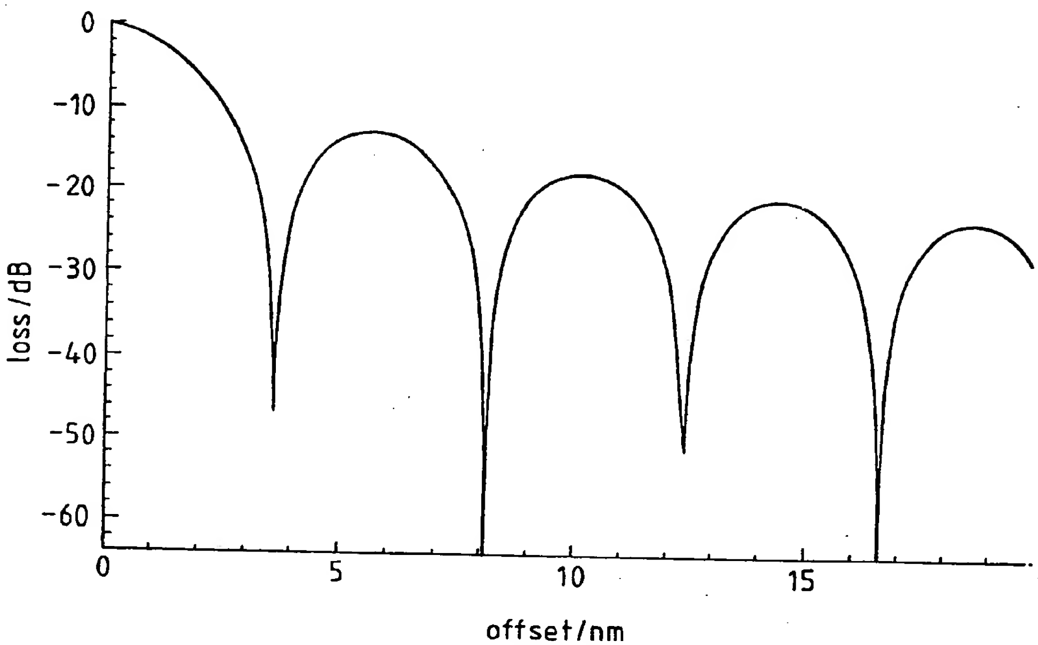


Fig.6.



European Patent Office

EUROPEAN SEARCH REPORT

Application Number

EP 88 30 9138

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.4)
Y	GB-A-2 168 215 (SECRETARY OF STATE FOR DEFENCE) * Figures 1,2,7; page 1, lines 116-130; page 2, lines 1-84; page 3, lines 22-63 *	1	G 02 B 6/34
A		2,3,4,7	
Y	ELECTRONICS LETTERS, vol. 17, no. 4, 19th February 1981, pages 165-167, London, GB; V. NEUMAN et al.: "Guided-wave holographic grating beam expander-fabrication and performance" * Figure 1; page 165, column 1, lines 11-14; column 2, lines 1-22 *	1	
A,D	US-A-4 671 603 (J.A. McQUOID et al.) * Figures 1,3,4; column 3, lines 57-68; column 4, lines 1-31; column 5, lines 45-68; column 6, lines 1-25 *	1,4,5	
A	SOVIET JOURNAL OF QUANTUM ELECTRONICS, vol. 16, no. 2, February 1986, pages 291-293, American Institute of Physics, Woodbury, New York, US; A.S. SVAKHIN et al.: "Dispersive device on polished cladding of a single-mode fiber waveguide" * Figure 1 *	1,6	TECHNICAL FIELDS SEARCHED (Int. Cl.4) G 02 B 6/00 G 01 J 3/18 G 03 H 1/04 H 04 J 15/00
A	DE-A-2 930 681 (LICENTIA) * Figure; page 4, lines 10-36; page 5, lines 1-5 * -/-	1,8	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	11-01-1989	MATHYSSEK K.

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

European Patent Office

EUROPEAN SEARCH REPORT

Application Number

EP 88 30 9138

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.4)
A	OPTICS LETTERS, vol. 10, no. 6, June 1985, pages 303-305, Optical Society of America, New York, US; D.J. McCARTNEY et al.: "Position-tunable holographic filters in dichromated gelatin for use in single-mode-fiber demultiplexers" * Figure 3; page 303, column 1, lines 12-16 *	1,5	
			TECHNICAL FIELDS SEARCHED (Int. Cl.4)

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	11-01-1989	MATHYSSEK K.

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document